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14. ABSTRACT
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SPECTRAL IRRADIANCE CALIBRATION IN THE INFRARED. XVII. ZERO-MAGNITUDE BROADBAND FLUX REFERENCE FOR VISIBLE-TO-INFRARED PHOTOMETRY

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ABSTRACT

The absolutely calibrated infrared (IR) stellar spectra of standard stars described by Engelke et al. are being extended into the visible and will span a continuous wavelength range from ~0.35 μm to 35.0 μm. This paper, which is a continuation of the series on calibration initiated with Cohen et al., presents the foundation of this extension. We find that due to various irregularities Vega (α Lyr) is not suitable for its traditional role as the primary visible or near-infrared standard star. We therefore define a new zero-point flux that is independent of Vega and, as far as is feasible, uses measured spectral energy distributions (SEDs) and fluxes derived from photometry. The calibrated primary stars now underpinning this zero-point definition are 109 Vir in the visible and Sirius (α CMa) in the infrared. The resulting zero-point SED tests well against solar analog data presented by Rieke et al. while also maintaining an unambiguous link to specific calibration stars, thus providing a pragmatic range of options for any researcher wishing to tie it to a given set of photometry.

Key words: standards – stars: general – techniques: photometric – techniques: spectroscopic

Online-only material: machine-readable and VO tables

1. INTRODUCTION

Vega has historically been used as the primary standard to which photometric and spectroscopic work on other stars is referred (e.g., Hearnshaw 1996). Therefore, various experiments in the 1970s through the 1980s attempted to establish the absolute calibration of Vega between 0.32 and ~4.5 μm by direct comparison of its stellar flux with laboratory blackbodies. The discovery by the *Infrared Astronomy Satellite* (*IRAS*) of excess 60 μm and 100 μm emission from Vega due to a cool debris disk surrounding the star (Aumann et al. 1984) and of smaller (5%–10%) apparent excesses of uncertain origin between 2.2 and 4.9 μm found in calibrations performed in the Canary Islands (Blackwell et al. 1983; Mountain et al. 1985; Booth et al. 1989) undermined the value of Vega for infrared (IR) calibration. Additional factors described in Section 2, including an anomalously high luminosity, unusual line profiles, possible identification as a λ Boo star, and evidence for variability, suggest that Vega is not suitable to define the primary zero-point flux calibration, even in the visible.

We therefore define a new zero-point flux that is independent of Vega and, as far as possible, uses measured spectral energy distributions (SEDs) and fluxes derived from photometry (Section 3). For the zero-point spectrum in the visible we adopt the spectrophotometry of Tüg et al. (1977) for 109 Vir scaled by the *V* magnitude of 3.74 (Mermilliod 1991) onto which we overlay the Pickles (1998) template of an A0 V star. We adopt Sirius as the infrared standard, first creating an empirical near-infrared template between 0.8 and 2.5 μm by averaging calibrated spectral observations of eight A stars (rescaled to A0 V) observed by Bohlin & Cohen (2008) and then emplacing the result over the near-infrared photometry of Sirius scaled to zero magnitude. We do the same for the 2.38–9.4 μm Short Wavelength Spectrometer (SWS; de Graauw et al. 1996) spectrum of Sirius. As a spectral interpolative device beyond 9 μm we multiply a Kurucz model spectrum of Sirius by $(\lambda/8)^{0.027}$ in order to optimize the fit through the calibrated data in the individual *Midcourse Space Experiment* (*MSX*) bands longward of 8 μm. The result is a zero-point SED between 0.35 and 1 μm gridded at a spectral resolution of 0.0005 μm; the resolution monotonically increases at wavelengths longer than 1 μm.

We test this new zero-point SED by integrating a solar-model spectrum and the zero-point SED over near- and mid-infrared radiometric bands and compare the results to the solar analog and A-star color data tabulated in Rieke et al. (2008) for these bands. Our results match those values with a level of consistency (rms 0.4%) even better than that obtained using the zero-point definition in Rieke et al. (rms 1.6%).

Although the calibration presented in this paper agrees well with that of Rieke et al. (2008) in terms of the stated uncertainties, there are several notable differences which are discussed in Section 4. One is the methodology: we have used observed values directly whenever possible rather than adopting a modeled SED fit through the photometric observation. Thus, the zero-point flux that underpins the extension of the absolute flux of the stellar standards from the near-infrared into the visible is entirely based on observational information. The second is that we adopt the independent calibrations for each of the *MSX* mid-infrared bands rather than combining the three 8–14 μm bands. Third is that although our calibration deviates from that of Rieke et al. by up to 3% over the spectral range 0.7–30 μm, it improves the band by band match with that expected from the solar analog method. Finally, the new zero point provides a more direct tie to observed data through a chain of measurements to Sirius or 109 Vir, observations of which can in turn be used to tie new observations unambiguously to the system.

2. VEGA: A PROBLEMATIC STANDARD

2.1. *The Spectral Energy Distribution*

Vega has long been considered the primary photometric and spectroscopic standard in the visible and infrared. Hayes (1985) and Megessier (1995) separately reviewed the results of the absolute calibration experiments from the 1970s and 1980s, culling and correcting the values before taking a weighted average. The resulting proposed best estimates of 3.44×10^{-12} W cm^{-2} μm^{-1}$\pm$1.5% and 3.46×10^{-12} W cm^{-2} μm^{-1}$\pm$ 0.7%, respectively, agree to within 0.6%. One or the other value is typically taken to provide the necessary absolute scaling for relative photometry and spectrometry in the visible range.

As infrared astronomy developed, Vega initially continued to be the reference object of choice. However, the discovery by *IRAS* of excess 60 μm and 100 μm emission from a cool debris disk surrounding Vega (Aumann et al. 1984) was the first definitive sign that it might not be an appropriate calibration standard for infrared work. Nevertheless, emission from the $\sim$100 K circumstellar material should not contaminate the spectrum much below 12 μm (e.g., Price et al. 2004a).

Thus, when Cohen et al. (1992) began a multi-year effort to build calibrated composite SEDs for IR standard stars, they used what they deemed the best available theoretical model of Vega to transfer the Hayes visible flux estimate ($3.44 \pm 0.05 \times 10^{-12}$ W cm^{-2} μm^{-1}) by extrapolation to infrared wavelengths out to 15 μm. The R. Kurucz theoretical spectral model provided to them especially for the purpose in 1991 used a specifically tailored metallicity and a finely gridded wavelength scale into the infrared (see Kurucz 1991). The model parameters were $T_{\rm eff} = 9400$ K, log(g) = 3.90, and [Fe/H] = -0.5, which result in a diameter of $\theta = 3.335$ mas when scaled to the Hayes flux at 0.5556 μm. Cohen et al. also obtained a similarly tailored Kurucz theoretical model for Sirius and normalized its SED to the calibrated Vega model using relative photometry between Sirius and Vega at eight photometric wavebands between 2.2 and 12 μm. The thus calibrated Sirius SED was intended for use at those IR wavelengths where Vega is too faint or at which the excess emission influenced the flux. The resulting Sirius model parameters are $T_{\rm eff} = 9850$ K, log(g) = 4.25, [Fe/H] = +0.5, and $\theta = 6.04$ mas. We refer to these two Kurucz models as the "CWW Vega" and "CWW Sirius" models. (Note that the Sirius model SED was increased by 1% in Paper XV of the series (Price et al. 2004a) and subsequent reference to CWW Sirius in our tables and figures indicates the SED including the 1% adjustment. This 1% bias may have arisen from the large wavelength range over which Cohen et al. normalized Sirius to Vega, as Vega's measured SED has a slightly increasing IR flux with wavelength compared to the Sirius SED, making the ratio dependent on the IR bands selected.)

Cohen et al. assigned the same 1.45% uncertainty to their IR calibration for Vega as Hayes (1985) did for the 0.5556 μm flux. That is, Cohen et al. assumed no uncertainty due to the models used to extrapolate between the visible and IR. Castelli & Kurucz (1993, 1994) later derived updated models for Vega with $T_{\rm eff} \sim 9550$–9650 K, depending on the reddening assumed. Since the IR SED for a 9550 K model tied to the 0.5556 μm flux falls 2% below the $T_{\rm eff} = 9400$ K model used by Cohen et al., a bias of at least 2% for the CWW Vega and Sirius spectra in the IR due to the choice of models might have been appropriately factored in. However, this 2% change introduced by the Castelli & Kurucz model is in the wrong direction as far as direct calibrations in the IR indicated. The Kurucz 9400 K model used by Cohen et al. (1992) is certainly more consistent than warmer models with the direct IR calibration measurements of Blackwell et al. (1983). Blackwell et al. assessed the fit of various Vega models to the combination of the Hayes & Latham (1975) visible calibration and their own direct calibrations at 1.2 μm, 2.2 μm, 3.7 μm, and 4.6 μm against a blackbody and concluded that the best fit was for a cool, $T_{\rm eff} = 9300$ K, Dreiling & Bell model (1980) and speculated that a cooler model might remove the assumption that Vega had infrared flux excess as proposed by Selby et al. (1983). The Megessier (1995) compilation of IR calibrations in the J to L range average $\sim$3% higher than the 9400 K Vega model predictions (also see Figure 5 of Hayes 1985) or $\sim$5% above the 9550 K Vega model of Castelli & Kurucz (1994).

However, more problematic is that Vega has proven in many ways to be anything but a typical A star. For one thing, the colors of Vega do not match those of other A0 stars. Megessier (1995) notes that it is brighter than the A0 V star average from Johnson (1966) at the J band and longer wavelengths while fainter at R and I bands. This seems to suggest that while Vega's SED is bluer than that of other A0 stars between V and I in a manner that corresponds to that of a star some 1000 K hotter than the A0 mean based on Bessel's (1979) Table II, it seems to be cooler than average by $\sim$650 K from 1 to 5 μm.

The absolute *Hipparcos* visual magnitudes of Jaschek & Gomez (1998) indicate Vega was about 0.5 mag brighter than the average for A0 V stars (Petrie 1964; Millward & Walker 1985; Jaschek & Gomez 1998), which corresponds to a luminosity $\sim$60% above the average. Both old (e.g., Hanbury Brown et al. 1967) and new (e.g., Kervella et al. 2003; Peterson et al. 2006) interferometric observations indicate Vega has a much larger diameter than Sirius. Near-IR interferometric data also suggest the presence of a hot inner disk (e.g., Ciardi et al. 2001; Absil et al. 2006), in addition to the cooler disk discovered by *IRAS* (and detected at wavelengths as short as 12 μm; Price et al. 2004a).

Spectroscopically, Vega shows various irregularities in its lines: asymmetries attributed to intervening interstellar material (Griffin 2002), possible contributions from emission lines similar to those seen in variable stars (Wisniewski & Johnson 1979), and weak metal lines showing square bottomed profiles (e.g., Gulliver et al. 1994). Gray (1985, 1988) suggested that Vega is a pole-on, highly oblate, rapid rotator to explain the excess in magnitude. Thus, the star exhibits extreme limb darkening and a large decrement in effective temperature from pole to equator. Much support has accumulated for this scenario (e.g., Peterson et al. 2006), including recent modeling by Aufdenberg et al. (2006) to account for the K'-band interferometric measurements. These authors find that the best fitting model ($T_{\rm eff}$_pole = 10150 K, $T_{\rm eff}$_eq = 7900 K, $\theta = 3.329$ mas) has the pole inclined 5° to line of sight and rotates at 91% of the angular speed of break-up, resulting in a temperature drop of 2250 K from center to limb. Although the total luminosity predicted by the Aufdenberg et al. (2006) model is about average for a non-rotating A0 star, it is emitted in a highly non-homogeneous manner with five times more UV flux being emitted from the pole as is emitted in the equatorial plane, while the visible through near-IR flux is some 70% greater at the pole than that of the equatorial plane and 54% greater than that expected from a slow or non-rotating A0 V star.

Bohlin & Gilliland (2004) used the *HST* Space Telescope Imaging Spectrograph to obtain a 0.17–1.01 μm spectrum of Vega calibrated relative to a set of white dwarf models. They normalized the spectrum to Megessier's 0.5556 μm flux of 3.46×10^{-12} W cm^{-2} μm^{-1} and noted the good correspondence between their measurement and a Kurucz 2003 model with $T_{\rm eff} = 9550$ K for wavelengths greater than 0.42 μm. However, the measured spectrum exceeded the theoretical one at both longer and shorter wavelengths (particularly after additional instrumental corrections were applied (Goudfrooij et al. 2006;

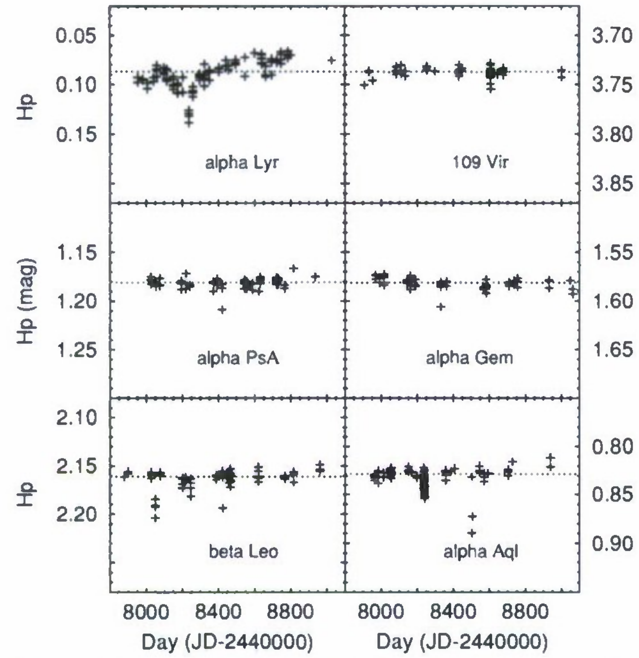

Figure 1. *Hipparcos* H_p magnitudes for six A stars: α Lyr, 109 Vir, α PsA, α Gem, β Leo, and α Aql. The dashed lines show the mean magnitude and uncertainty for each star: 0.087 ± 0.002, 3.7371 ± 0.0005, 1.1808 ± 0.0007, 1.5811 ± 0.0009, 2.1605 ± 0.0006, and 0.827 ± 0.001 mag, respectively. Uncertainties on the individual data points are almost all smaller than the symbol size. The corresponding scatter about the mean for each star is 0.014, 0.004, 0.004, 0.005, 0.005, and 0.006 mag, respectively. The Vega H_p mean magnitude of 0.087 ± 0.014 is much fainter than the expected 0.033 ± 0.01.

Bohlin 2007), as Aufdenberg et al.'s (2006) rapid rotating pole-on model qualitatively predicts.

2.2. Variability

Vega also seems to exhibit intermittent variable behavior. The two and a half years of *Hipparcos* H_p measurements for Vega between 1990 and 1993 averaged to 0.0868 ± 0.002, though a value of 0.033 was expected from Mermilliod's 1991 version of online *UBV* homogeneous means (Mermilliod & Mermilliod 1994,[3] Mermilliod et al. 1997). Other A stars had their appropriate expected H_p magnitudes. The time series of the 90 *Hipparcos* measurements of Vega (Figure 1) displays variations of more than 6% about the mean during the mission. We do note that Vega was one of the three stars mentioned in the *Hipparcos* explanatory supplement (ESA 1997) as having discrepant brightnesses compared to their expected *V* magnitudes. While that might be attributed to saturation effects, other, brighter stars do not show such discrepancies between *V* and H_p. Hence we conclude that the faintness of Vega cannot be attributed to non-linearity in *Hipparcos*.

Measurements in a broad waveband similar to *R* by the Solar Mass Ejection Imager (SMEI; Eyles et al. 2003 and Jackson et al. 2005 describe the SMEI hardware and mission, respectively) from 2003 to 2006 provided by S. Spreckley (2008, private communication) show no significant variation. However, the SMEI 0.7 μm magnitude for Vega relative to the SMEI Sirius magnitude of -1.46 and 3.75 for 109 Vir averaged to -0.028 ± 0.003, or $\sim$0.06 mag brighter than the expected 0.033.

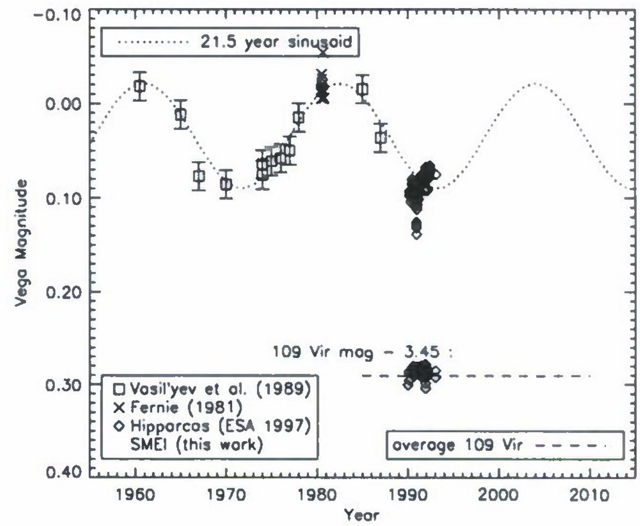

Figure 2. Long-term variability of Vega. Symbols are data from the following references: squares: Vasil'yev et al. (1989) and references therein; crosses: Fernie (1981); diamonds: *Hipparcos* (ESA 1997); dots: SMEI (this work, see the text). The dashed line shows a 21.5 year sinusoid, similar to the 23 year period suggested by Vasil'yev et al. The *Hipparcos* and SMEI data for 109 Vir are also shown (offset by 3.45 mag). The increased scatter on the SMEI data is due to the relative faintness of 109 Vir.

The *Hipparcos* Vega measurements vary between 0.065 and 0.14 mag, which are among the dimmest values reported in the literature; in contrast, the SMEI values were among the brightest. A literature search reveals that the constancy of Vega has been questioned since at least the late 1970s (e.g., Fernie 1976; Wisniewski & Johnson 1979; Fernie 1981; Vasil'yev et al. 1989). Wisniewski & Johnson (1979) commented that: "...Our photoelectric photometry, which was begun in 1950, shows that Vega has continued to vary by about the same amount [0.08 mag] that Guthnick found in 1931, but for the time being our data are too scattered to yield any period."

Both short- and long-term variations in Vega have been suggested. Fernie (1981) compared Vega to the nearby references ε_1 Lyr and ε_2 Lyr over a 4 month period. He found Vega to have an average magnitude $V \approx -0.017 \pm 0.006$ mag (measured relative to ε_1 Lyr) but the extremes of -0.06 and ~ -0.03 mag were not included in the 3σ uncertainty. In contrast, the ratios of the reference stars to each other remained constant to $3\sigma = \pm 0.003$ mag, with no rejected data. Guthnick (1931) reported that the brightness of Vega varied irregularly both rapidly (in hours) and slowly (over months) during his 17 years of observation. He noted rapid variations of 0.08 mag, while the slow variation resulted in the mean magnitude ranging from 0.03 in 1917 to 0.08 in 1930. He also reported a brightening by 4% in only 2 hr (his unnumbered figure on p. 25; reproduced by Wisniewski & Johnson 1979).

Vasil'yev et al. (1989) also reported long-term variations in the mean Vega fluxes in the twelve 0.5556 μm flux determinations by previous researchers over a 25 year period. These fluxes varied by 10% about a mean of 3.53×10^{-12} W cm^{-2} μm^{-1}, a value significantly greater than that given by either Hayes or Megessier. When plotting the flux as a function of observation date, Vasil'yev et al. found the data could be fit to first order by a cosine with a period of $\sim$23 years (their Figure 1). Figure 2 shows an updated version of the plot

[3] Available through Vizier: http://vizier.cfa.harvard.edu/viz-bin/VizieR?-source=II/168; the 1997 version does not seem to be in Vizier.

using the more recent data, including that from Fernie (1981), *Hipparcos*, and SMEI. The subsequent data are consistent with the 23 year estimate, although a 21.5 year period fits slightly better.

The low metallicity and abundance pattern in Vega have also led to the suggestion that it may be a λ Boo star (Baschek & Slettebak 1988; Ilijic et al. 1998). These objects have peculiar abundances and often show variability and infrared excess, although the mechanism(s) responsible for these characteristics are a matter of debate (e.g., Paunzen et al. 2003; Moya et al. 2009). Recent modeling by Yoon et al. (2008, 2010) supports the identification of Vega as a member of this poorly understood class of stars. Taken in sum, the observational characteristics of Vega, as well as its intrinsic properties as revealed by modeling and simulation, make it a problematic choice for a primary calibrator in either the visible or infrared.

3. TRACING A CALIBRATION TO WELL-BEHAVED STANDARD STARS

To replace Vega, we use 109 Vir, scaled by its apparent magnitude, for the visible flux zero point because Tüg et al. (1977) obtained absolute spectrophotometry on this star with the same techniques that they used to measure Vega itself. For the infrared zero definition a modified Sirius modeled spectrum provides the backbone onto which is overlain an averaged *Hubble* near-IR spectrum for A dwarfs. The mid-infrared Sirius spectrum from the SWS on the *Infrared Space Observatory* (*ISO*; Kessler et al. 1996) provides the mid-IR zero point while the model, adjusted to fit the *MSX* absolute calibration (Price et al. 2004a), is used beyond 9 μm.

3.1. 109 Vir: the Proposed New Primary Visible Standard

In contrast to Vega's peculiarities, most of the brighter early A-type stars appear to be quite steady over the same time period in the *Hipparcos* plots (Figure 1). The A0 V star 109 Vir ($V = 3.736$, $H_p = 3.737$) shows a scatter of 0.004 mag in the *Hipparcos* H_p data as compared to a 0.014 mag scatter for Vega. Unlike Vega, 109 Vir has essentially the same listed H_p magnitude as V magnitude (Mermilliod 1991) which suggests stability across widely separated times.

Tüg et al. (1977) directly calibrated 109 Vir and Vega from 0.34 to 0.988 μm against blackbody standards at the telescope and cite errors of 1% at $\lambda > 0.4\,\mu$m and 2% below "if there are no known systematic errors." Because of this calibration, Philip & Hayes (1984) deemed 109 Vir as second only to Vega in its credentials as a standard star, and rate it more generally useful because it is ~3.7 mag fainter. When the stability of Vega was called into question (again) around 1980, the non-variability of the 109 Vir flux became of increased interest. Taylor (1982, 1984) raised the possibility that 109 Vir might also be variable. Therefore, Philip & Hayes analyzed 40 photometric observations made in the 4 color *uvby* system on 29 nights spread over the years 1969, 1970, 1971, and 1978. They also obtained a second set of 0.345 and 0.679 μm spectrophotometric observations between 1978 and 1980. From these observations they conclude there was no evidence of variability for this star in the multi-year database. Adelman (1997) also found no variability in his 4 years of *uvby* observations. Taylor (2007) later agreed that "there is no convincing evidence of variation in this key star [109 Vir] after 1975" based on data from 1990 to 1998.

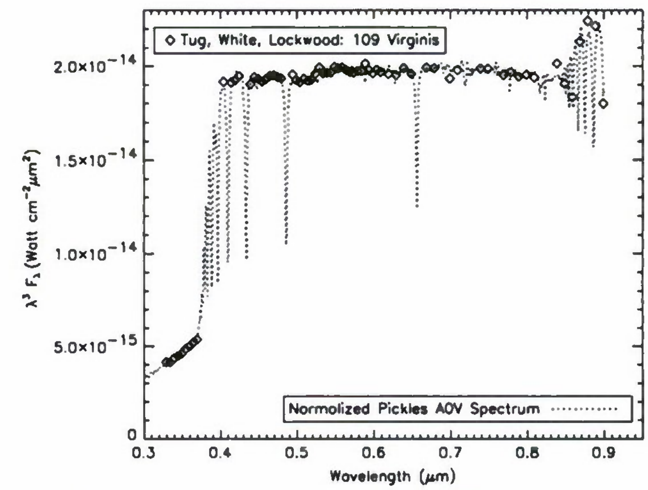

Figure 3. A0 V template (dotted line) from Pickles (1998) overlain on the Tüg et al. (1977) absolutely calibrated spectrophotometry (solid line) of 109 Vir.

To be used as a primary standard, 109 Vir should have zero mean colors and the SED of a prototypical A0 V star. Indeed, the Mermilliod (1991) value $B - V = -0.007$ for the star is the same as that for the effective temperature (9700 K) which corresponds to zero color for $V - R$ and $V - I$ in the Bessel (1979) Cousins *VRI* magnitude tables. Figure 3 shows the overlay of the Pickles (1998) A0 V template onto the absolute spectrophotometry of 109 Vir from Tüg et al. (1977). The result was multiplied by 31.218 to scale the 109 Vir (and the template) to zero magnitude across the resulting synthetic photometry on V, R, and I bands (as defined by Bessel 1979, 1990). Likewise, by Bessel's color definitions there are slightly non-zero colors at the shortest wavelengths: $B - V = -0.007$ & $U - B = -0.022$ (Mermilliod 1991). Below 0.45 μm, particularly around 0.4 μm, the Pickles A0 V template underestimates the Tüg et al. photometry, so we apply a small correction factor the template of the form $(\lambda/a)^b$, where $[a, b]$ are $[0.45, -0.4]$ for 0.38–0.45 μm and $[0.36, 1.1]$ below 0.38 μm, where λ is in microns.

3.2. The Infrared: NICMOS A Stars and SIRIUS

Although 109 Vir is well behaved in the visible, it is too faint in the infrared to have the high accuracy calibrated photometry needed to reliably extend the SED, with only a single set of *JHK* measurements found in the literature (Leggett et al. 1986).[4] Sirius is therefore the preferred standard at infrared wavelengths. It, however, is too bright in the near-IR for the only space-based spectrometer, the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) grism spectrometer on the *Hubble Space Telescope* (*HST*). Thus, we use measurements of A stars that NICMOS could safely observe to create the SED for the region between the long wavelength end of the 109 Vir spectrophotometry and the beginning of the SWS spectral region (see below).

3.2.1. NICMOS

Bohlin & Cohen (2008) measured the 0.8 μm to 2.5 μm absolute flux distributions for eight A-type stars (A1–A5) with NICMOS. They initially compared the spectra to the Kurucz-based template from Cohen et al. (2003) for each star, but

[4] We note that the raw data from a *Spitzer* observation of 109 Vir at 24 μm were recently made public but too late to be included in this analysis.

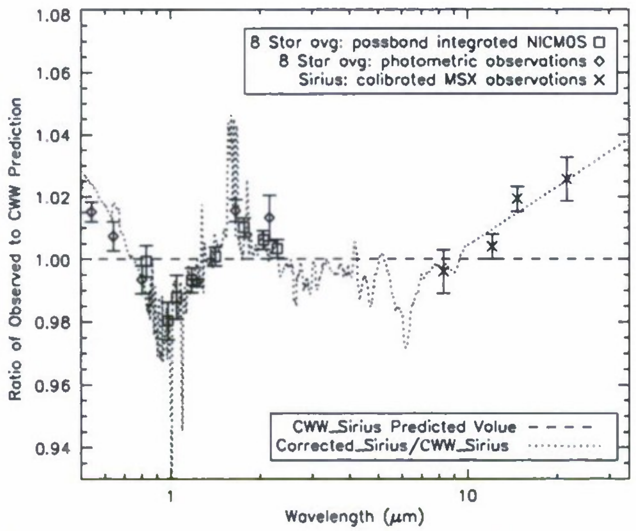

Figure 4. Comparison of the corrected Sirius SED to the CWW Sirius SED (dotted line). The squares show the mean of the eight A stars ratioed to their Cohen (2007) templates, based on Figure 1 of Bohlin & Cohen (2008, their large black circles), at the continuum ranges defined in their Table 2; similarly, the diamonds are the mean ratios for their ground-based photometry on the A stars relative to the Cohen templates (their red circles). The x's show the *MSX* photometry relative to synthetic photometry from the CWW Sirius model.

subsequently used updated models from Castelli & Kurucz (2004; CK04); these models significantly improved the match to the observed structure in the Brackett line-Brackett continuum transition region. Nonetheless, band-integrated comparisons of the NICMOS data showed similar patterns of discrepancy when compared with either the Cohen et al. (2003) or CK04 models. Bohlin and Cohen interpreted this to suggest that the NICMOS-based photometry revealed stars of cooler effective temperatures and lower extinctions which averaged $\Delta T \sim -500$ K and $\Delta E \sim 0.06$ relative to the values Cohen et al. (2003) had obtained by matching spectral features to MK standards.

In contrast to Bohlin & Cohen's interpretation that their observations are evidence of systematic spectral misclassification, we suggest the temperature-photometry mismatch is evidence that the models for a given effective temperature do not well represent the measured, calibrated infrared fluxes. Gray (1988, p. 338), in analyzing the effects of rotation on A-star spectra, noted, "the importance of the principle that spectral classification should be completely independent of photometry. Never change your spectral type just because the photometry disagrees with it! You might miss something important or interesting!" Here, we are concerned with not missing evidence of systematic distortions in the IR portion of the A-star models relative to the measured SEDs.

Bohlin & Cohen present ratios of the measurements to models based on Cohen et al. (2003) and from CK04 for ground-based $BVRIJHK_s$ photometry as well as the bands they define specifically for continuum regions in the NICMOS spectra. We take the average of these ratios from their Figure 1 as the best representation of the smoothly varying deviations of the measurements from the models.[5] The rms scatter between the eight star ratios obtained at each effective wavelength is about 1.5%, so the reduced internal uncertainty in the average should be about 0.5% at each data point. Figure 4 shows this average deviation relative to the CWW Sirius model, with discrepancies of 2%–3% (0.02–0.03 mag). The error bars range from $\sigma = 0.003$ to 0.007, so the structure is significant to about 5σ. The largest deviations appear in the Brackett & Paschen overlap region, which may reflect issues in the line opacities of the models, as Bohlin & Cohen noted in their discussion.

[5] Using the ratios from their Figure 2 does not change the derived deviations because the continuum wavelengths are in regions where the models do not differ enough to affect the results.

Table 1
Sirius SWS Normalizations

Wavelength Range (μm)	Normalization Factor
2.400–2.553	$0.947(\lambda/2.5)^{-0.2}$
2.553–2.9893	0.95
2.9893–2.99	0.98
2.99–4.01	0.985
4.01–5.24	0.915
5.24–6.938	$0.871(\lambda/6)^{-0.05}$
6.938–9.4	0.875

To rectify these discrepancies from the CWW Sirius model, we therefore replace the near-IR portion of the zero-point SED based on the NICMOS data. We splice the NICMOS data averaged from the eight A stars of Bohlin & Cohen after scaling to Sirius and adjusting the slope slightly (i.e., multiplying by λ^{ε} where $\varepsilon = -0.22$ for $\lambda < 1.5\,\mu$m and $\varepsilon = -0.12$ for $\lambda > 1.5\,\mu$m) to match the segment endpoints and the guiding data in between. This gives an empirically based SED for the 0.9–2.4 μm portion of the spectrum adjusted to the colors of the spectrophotometric calibration used by Bohlin & Cohen.

3.2.2. *SWS*

Between 2.4 μm and 9.4 μm, a Sirius spectrum (Target Dedicated Time number 68901202; Sloan et al. 2003) measured with the SWS on *ISO* is spliced to the NICMOS data. The *ISO* SWS relative spectral response curves were originally calibrated on the ground, then were adjusted on-orbit using stars with reference spectra from Kurucz and Uppsala model atmospheres (Cohen et al. 1992 and Decin 2000, respectively) for a range of spectral types (Vandenbussche et al. 2003). The archival data were later modified to account for the underestimation of CO and SiO absorption band strengths in the atmospheric models (Price et al. 2002). These corrections were applied using smooth distortions of the original response. Therefore, local relative detail is expected to be reliable, given a sufficiently high signal-to-noise ratio.

The SWS segments from Sloan et al. (2003) (the "pws" data) are spliced to the NICMOS data at 2.4 μm and to each other using the normalization factors in Table 1. Two segments, 1A and 2B, required small wavelength-dependent adjustments that are specified in the table (see Price et al. 2004b for details regarding the normalization and wavelength-dependent adjustments necessary to rationalize the Sloan et al. pws data). The SWS pipeline and the Sloan post-processing applied wavelength-dependent factors to the raw data to mitigate instrumental effects such as the nonlinear "memory effect" seen in Band 2 (4–12 μm) and 4 (27.7–45 μm, which is not used here) in bright sources (e.g., Fouks & Schubert 1995; Fouks 2003; Kester 2003); Band 1 is not affected. These effects manifest as differences in the two scan directions, often as a change in slope for a portion of the segment, as is the case for the Sirius spectrum in Bands 2A and 2C. This effect contributes ~2%–3% uncertainty in the 4–5.24 and 7–9.4 μm regions of the spectrum.

3.2.3. *Beyond 9.4 μm*

The SWS portion of the SED is limited to 9.4 μm as the SWS data become noisy beyond $\sim$9.5 μm and the 10–12 μm region is much more affected by the memory effect. Therefore, a model must be used beyond 9.4 μm. Harkening back to the discussion in Section 2.1, the question becomes, what is the appropriate model to use? The highly accurate ($\sigma \sim \pm$ 0.5%) *MSX* absolutely calibrated values (Price et al. 2004a, their Table 9) indicated a trend in which the measured/predicted flux ratio systematically increases with wavelength longward of $\sim$10 μm, as seen in Figure 4. The reduced χ^2 of these four data points relative to prediction of the original CWW Sirius is about 7.4. If the Sirius spectral flux is raised uniformly upward by the 1.1% mean bias in the *MSX* data as recommended by Price et al., the reduced χ^2 is 5.4. However, the best linear fit of flux versus wavelength through the *MSX* data gives χ^2 = 1.7. Thus, within the uncertainties, the *MSX* calibration indicates an approximately linear trend to the deviation from CWW values. However, substituting a cool enough ($T_{\rm eff} \ll$ 9850 K) Kurucz model that matches the *MSX* data between 8 and 20 μm would produce large discrepancies in the fit with observed Sirius data at short wavelengths. We are faced with either rejecting the apparent trend or accepting it as an indication of systematic divergence between the model SEDs and real values in the IR.

When considering the role of model comparisons to well-calibrated data, Hayes (1985, p. 227) notes, "Firstly, the degree of fit can be used to diagnose problems with the models and to improve the physics and the method of calculation. Secondly, the fitting of the model energy distributions to observations can be used to obtain values for fundamental stellar parameters such as effective temperatures and surface gravities." In the current case, we are most concerned with using the data in the first role. R. Kurucz has been refining his atmospheric models continuously for the past few decades, particularly in the visible and near-IR, taking advantage of improvements in the underlying physics and the available computing resources (e.g., Kurucz 2005a, 2005b; Bohlin & Cohen 2008). Comparisons with other independent models show that differences can occur as a result of uncertainties in the modeling process. Such was the case, for example, between the white dwarf models of Hubeny and those of Koester/Finley[6] studies by Bohlin (2000). Comparison of those models showed persistent patterns of disagreement with wavelength for stars over temperatures ranging from 30,000 K to 60,000 K. Bohlin warned, "until this problem is resolved, these differences in the implementation of basic physics must be included in the uncertainties of the [model-based] absolute flux calibrations."

We therefore adjust the shape of the Sirius SED to approximately follow the linear trend detected by *MSX* by multiplying the 9850 K CWW model by $(\lambda/8)^{0.027}$ in the 9.4–35 μm region. Questions are certainly raised by such tinkering. How robust are the models in the infrared? No accurate absolute calibration measurements exist in this spectral region after 1985 outside of Rieke et al. (1985) and Price et al. (2004a). Can this change be supported by an independent check?

[6] Bohlin (2000) does not give references for the Koester/Finley and Hubeny models, as they seem to have been provided to him via personal communication, but contemporaneous publications are Finley et al. (1997) and Hubeny et al. (1999).

4. DISCUSSION

4.1. *Solar Analog Consistency Check*

The Sun is the most closely studied star and its spectrum may be regarded as an independent standard reference. Multi-wavelength flux calibrations of the Sun have been performed at a very different intensity level than were those on distant stars. The semi-empirical models developed to represent the SED of the Sun were informed by detailed knowledge obtained over a wide range of wavelengths and size scales and, furthermore, involve very different atmospheric modeling physics than the A star models we have discussed above. Therefore, it would be a semi-independent validation of our proposed zero-point SED if comparison of A-star and solar-analog-based photometry showed good agreement, since any biases would not be expected to be shared. Two carefully constructed tables of solar analog colors are available: Bessel et al. (1998, their Table A3) for the wavelengths shortward of 1 μm in the Cousins *UBVRI* system and Rieke et al. (2008, their Table 3) for wavelengths beyond 1 μm (2MASS, Two Micron All Sky Survey, JHK_s, Cutri et al. 2003; IRAC [8], Fazio et al. 2004; MIPS [24], Rieke et al. 2004). Both sets of solar analog colors are determined relative to "average" A-star photometry used by the authors to set the zero color definition. However, different collections of A-stars and solar-type stars were averaged in each case. Rieke et al.'s Table 11 lists 2MASS JHK_s and *Hipparcos* *V* colors for 57 A0 V stars and defines their average colors with an internal precision of $\pm$0.003 mag. The solar analog colors (their Table 3) were developed from a similar list (36 stars, their Table 12) and the color averages determined to within a random error of $\pm$0.008 mag. The solar colors are then rescaled such that A0 stars have zero color (or rather, the averaged colors from their Table 11 are subtracted from the averaged solar analog colors of their Table 12). For color differences taken purely within the IR range Rieke et al.'s (2008) average A star colors included A types other than A0, so Rieke et al.'s K_s-[24] 24 μm zero point for solar analog colors is determined relative to a mix of A-type stars ranging from A0 to A6. The Bessel (1979) Cousins *VRI* color table defines differences of 0.0 mag longward of *V* for a star of approximately 9700 K (that is, 60% of the temperature difference between A0 and A1 in their Table II). The average star implied by the photometry below 1 μm should then well match the shape of our $T_{\rm eff}$ = 9700 K standard for this wavelength range, 109 Vir.

The Kurucz model "ASUN"[7] well represents the present understanding and knowledge of absolute solar flux from the UV to the IR. This model spectrum was designed to be consistent with Neckel & Labs (1981, 1984) in the visible, with Thuillier et al. (2003) in the near-IR (Fiorenza & Formisano 2005[8]), and with the semi-empirical model C of Vernazza et al. (1981) out to 100 μm. Adopting this solar SED scaled such that integrating the flux reproduces the solar constant 0.1367 W cm^{-2}, we can then perform synthetic photometry in various bands and calculate solar colors with respect to our new zero-magnitude reference spectrum.

The top half of Table 2 shows that the 109 Vir-based zero reference spectrum results in solar colors which agree well with

[7] http://kurucz.harvard.edu/sun.html, fsunallp.1000resam251.

[8] Fiorenza & Formisano (2005) compare the Kurucz solar model with additional measured and theoretical spectra in the 1–5 μm range and discuss reasons for some of the differences. They conclude that the Thuillier et al. SOLar SPECtrum (SOLSPEC) measurements and the Kurucz model are the best available spectra in the 1–5 μm range.

Table 2
Solar Magnitude Predictions Using the Proposed Zero Reference

Photometric Bands	Solar Magnitude[a]	Kurucz Model Solar Synthetic Photometry	Δ	Rieke et al. (2008) Solar Synthetic Photometry	Δ
Johnson *U*	−25.886	−25.943	...	−25.970	...
Johnson *B*	−26.071	−26.052	−0.019	−26.059	−0.012
Johnson *V*	−26.723	−26.723	0.0002	−26.705	−0.018
Cousins *R*	−27.078	−27.084	0.006	−27.070	−0.008
Cousins *I*	−27.415	−27.412	−0.003	−27.412	−0.003
Mean Δ ± rms			−0.005 ± 0.013		−0.011 ± 0.007
2MASS *J*	−27.881	−27.886	0.005	−27.893	0.012
2MASS *H*	−28.207	−28.206	−0.0008	−28.235	0.028
2MASS *K*	−28.268	−28.265	−0.0028	−28.306	0.038
[8]	−28.314	−28.318	0.0042	−28.337	0.023
[24]	−28.313	−28.312	−0.0008	−28.332	0.019
Mean Δ±rms *J,H,K*,[8],[24]			0.001 ± 0.003		0.024 ± 0.010

Notes. [a] Solar *V* magnitude, generated from ASUN normalized with the zero-point SED from this work, is transferred to the other bands with the solar colors from Bessel et al. (1998) for *UBVRI* and Rieke et al. (2008) for *JHK*[8][24].

Table 3
Solar Magnitude Predictions Using "Vega" from Rieke et al. (2008)

Photometric Bands	Solar Magnitude[a]	Kurucz Model Solar Synthetic Photometry	Δ	Rieke et al. (2008) Solar Synthetic Photometry	Δ
Johnson *U*	−25.887	−25.976		−26.004	
Johnson *B*	−26.072	−26.041	−0.031	−26.048	−0.024
Johnson *V*	−26.724	−26.724	0.0005	−26.706	−0.018
Cousins *R*	−27.079	−27.094	0.0155	−27.080	0.002
Cousins *I*	−27.416	−27.434	0.0185	−27.433	0.018
Mean Δ ± rms			0.001 ± 0.022		−0.006 ± 0.019
2MASS *J*	−27.882	−27.887	0.006	−27.894	0.013
2MASS *H*	−28.208	−28.219	0.012	−28.248	0.041
2MASS *K*	−28.269	−28.262	−0.0065	−28.303	0.035
[8]	−28.315	−28.290	−0.0245	−28.309	−0.006
[24]	−28.314	−28.302	−0.0115	−28.322	0.009
Mean Δ ± rms *J,H,K*,[8], [24]			−0.005 ± 0.014		0.018 ± 0.019

Notes. [a] Solar *V* magnitude, generated from ASUN normalized with the zero-point SED from Rieke et al., is transferred to the other bands with the solar colors from Bessel et al. (1998) for *UBVRI* and Rieke et al. (2008) for *JHK*[8][24].

the solar analog colors of Bessel et al. (1998, their Table A3). The relation of the ASUN solar SED to our SED agrees with the experimentally determined relative photometry of average solar and 9700 K A-star fluxes with a bias of −0.005 and an rms of ±0.013 over the *BVRI* bands. The calculated solar magnitudes from ASUN in the infrared[9] match the solar analog predictions of Rieke et al. (2008, their Table 3[10]) within an rms deviation of ±0.003 and a bias of 0.001 (lower half of Table 2). The agreement requires that Sirius is defined to have magnitude −1.368, which is comparable to the value of −1.360 used by Engelke et al. (2006). This agreement encourages confidence in the solar-analog data as well. The empirical support derived from this comparison means that, from Johnson B to MIPS [24], our final calibration is supported by data independent of the absolute calibration data used by Rieke et al. which had been transferred from Vega observations.

We make these same solar analog comparisons to synthetic magnitudes generated from the absolute solar spectrum created by Rieke et al. (2008). That spectrum, which they refer to as the "Thuillier/Engelke solar SED," uses the satellite-measured spectrum of Thuillier et al. (2003) below 2.4 μm and an updated Holweger & Müller (1974) model normalized to Thuillier et al. and an Engelke-function (Engelke 1992) beyond 2.4 μm. The agreement is again good, although the scatter is increased by ~1% (Table 3, last column). When comparing the *J*, *H*, *K*, [8], [24] infrared bands to the BVRI, the Rieke et al. solar spectrum shows a relatively larger bias verses the solar analog predictions of ~ −0.023, which is mostly due to the *H* and *K* bands. Bohlin (2010) noted that the Thuillier spectrum diverges by +4% from Kurucz and MARCS models near these wavelengths and attributed the problem to the Thuillier data. In contrast, Fontenla et al. (2006) had found discrepancies of a few percent between the Thuillier data and solar models in the near-IR and concluded that the models could not perfectly represent the range of physical conditions in the Sun which are sampled by the observations.

4.2. *Zero-magnitude Reference Flux: Visible–Infrared Synthesis*

The 109 Vir and corrected Sirius spectra are each renormalized to zero magnitude. The two spectra are then merged (at 0.9 μm) to create a single zero-magnitude reference SED for

[9] Using the 2MASS pass band definitions from Cohen et al. 2003 and the [8] and [24] pass bands from the Spitzer Science Center (http://ssc.spitzer.caltech.edu/irac/calibrationfiles/spectralresponse/) and (http://ssc.spitzer.caltech.edu/mips/calibrationfiles/spectralresponse/, respectively).

[10] Note that the stars Rieke (and we) used for this are only from the 2MASS Read-1 mode to avoid an offset between 2MASS modes; see the discussion in their Appendices B and D.

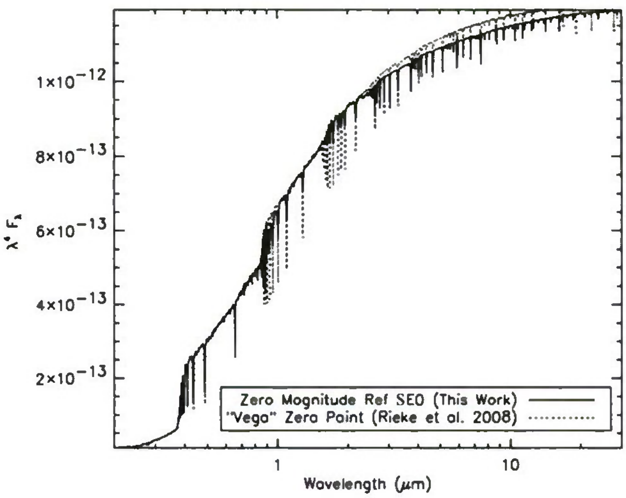

Figure 5. Comparison of the new zero-magnitude SED from this work (solid line) with the "Vega" SED from Rieke et al. (2008; dashed line).

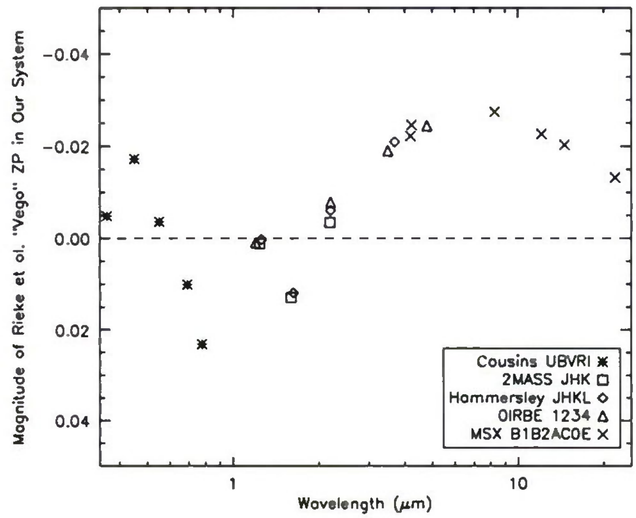

Figure 6. Synthetic photometry for Rieke et al.'s "Vega" reference SED in our new zero-magnitude SED definition.

use in the wavelength range 0.3–35 μm. The result is shown in Figure 5.

With this SED, the color ratios for bands grouped above or below 0.9 μm are accurate to ~1%, although the overall absolute flux uncertainty is about 2%. The error estimates are based on the uncertainties in the absolute calibration of 109 Vir as well as the possibility that 109 Vir or Sirius could be variable at the 1% level or less. Even if mild variability were present, the shape of the SED should remain well-defined. For bands between 2.4 and 8 μm (e.g., L, M, DIRBE 3 & 4, *MSX* B_1 & B_2), where there is no absolute photometry available, the absolute uncertainty is estimated to be ~3%, as is the Cousins *I* band; *U* band is uncertain to ~10%. These uncertainties correspond to integrated band magnitudes. Very narrowband or monochromatic calibrations depend on line-depths and shapes that are not known as accurately as the broadband colors.

4.3. *Comparison with the Rieke et al. "VEGA"*

If the new zero-magnitude reference flux agrees well with the solar analog table in Rieke et al. (2008), what is the distinction between the zero-point SED definition from this work and that which Rieke et al. proposed? The absolute zero-magnitude SED from this work is guided, as much as possible, by observed spectra, spectrophotometry, and photometry. The resulting SED is found to give closer agreement with the solar analog observations than does the Rieke et al. "Vega" zero point. Thus, our use of calibrated observations improves the relative fit with independent band-to-band color information.

Figure 6 shows the *BVRIJHK*, [8], & [24] band magnitudes of the Rieke et al. zero-point SED evaluated in our zero-magnitude system. Although the mean deviation is less than 1% and the rms about ±1.7%, the in-band flux does differ by almost 3% in some bands. Nevertheless, the magnitude definitions between the two zero point systems agree to within our estimated absolute uncertainties. This quantitative evaluation of the Rieke standard is important as some of the error analysis presented in that paper was dependent on calibration transfers through Vega which are suspect.

However, though the overall flux normalizations agree, the disagreements in local shape may be significant. The solar analog colors are determined to internal precision <1%. Table 2 shows that, when comparing synthetic solar magnitudes calculated using our absolute zero-point definition, we obtain band-by-band agreement to this precision. The corresponding synthetic solar magnitudes derived from the zero-point definition of Rieke et al., reproduced in Table 3, have twice the scatter in both the visible and infrared bands (which are calculated separately in the tables). Furthermore, the present analysis is based upon empirical data, which did not include the solar color analysis to derive the zero-magnitude SED. Thus the fact that the present zero-point flux improves upon the agreement with the solar colors is an independent validation of our zero-point definition.

Rieke et al. used a theoretical $T_{\rm eff} = 9550$ K Kurucz model to define their zero-point SED. They transferred all the IR calibration observations that they adapted, including their solar analog calibration, to a calculated equivalent flux value at 10.6 μm effective wavelength. The weighted average of all the independent flux determinations interpolated/extrapolated to that wavelength was used to adjust the absolute normalization of this "known" model spectral distribution. Given their assumption that the SED shape is theoretically defined, then the uncertainty of the overall SED is reduced by combining measurements at widely separated wavelengths since the absolute flux level is the only adjustable parameter. However, if the larger scatter with respect to the band-by-band solar analog predictions is a meaningful indicator, forcing the assumed shape may be distorting the data rather than filtering out noise, and local predictions may be less accurate.

Although the zero-point definitions derived by Rieke et al., and the present analysis, agree to within the stated uncertainties, and both used largely the same calibrated data, the calibration presented here better reflects the actual *MSX* calibration in each of the four mid-infrared bands. It also more faithfully accounts for the band-to-band flux ratios suggested by the high precision averaging of color differences by Rieke et al. and can be used to unambiguously transfer to new datasets since measurements on standard stars are directly tied to it.

5. SUMMARY

We have rejected Vega as the primary standard because it is a peculiar star (pole-on rapid rotator with a debris disk)

Table 4
Sample of the Zero-Point SED

Wavelength (μm)	Flux (W cm^{-2} μm^{-1})
1.00000	6.16357e-13
1.00010	6.15098e-13
1.00019	6.13964e-13
1.00029	6.12704e-13
1.00039	6.11383e-13
1.00049	6.10055e-13

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

and historically displayed variability. We adopt 109 Vir as the primary standard: we hang a Pickles (1998) A0 V SED template on the Tüg et al. (1977) absolute photometry and scale the result by the Mermilliod (1991) magnitude for 109 Vir to get the 0.35 – 0.9 μm zero-point SED. The CWW Sirius model is adopted as a backbone for the IR processing. The zero-point SED is extended to 2.4 μm using the average NICMOS grism spectra of eight early A stars, then to 9.4 μm using the *ISO* SWS spectrum of Sirius. Beyond 9.4 μm, out to 35 μm the CWW Sirius SED is adjusted to follow the linear trend detected by *MSX*. As a check, the solar analog colors predicted from our zero-point SED are compared to measured values, which validate the zero-point SED.

Although we use many of the resources used by Rieke et al., we (1) treat them differently and (2) add data not used by Rieke et al. (2008). As much as possible, we use observed information (109 Vir, NICMOS, *ISO* SWS), while Rieke et al. use a model SED. We use the absolute calibration in the four *MSX* mid-IR bands rather than the average from Price et al. (2004a) as was adopted by Rieke et al. (2008). Thus, the zero-point flux is defined by observations in the visible through mid-infrared and provides the backbone by which absolutely calibrated infrared (IR) stellar spectra of standard stars described by Engelke et al. (2006) are being extended into the visible to span a continuous wavelength range from $\sim$0.35 μm to 35.0 μm. Lastly, our chosen calibration data are not transferred through Vega and so is free of uncertainties introduced through that star's suspicious spectral and temporal behavior. The resulting zero-point SED, a portion of which is shown in Table 4, is available as an online accompaniment to this article.

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